Mode Optimization of a Meteorological Sensor using Taguchi Parameter Design

Alan Bell, Craig Brownell
ITT Industries, Space System Division
Fort Wayne, Indiana USA

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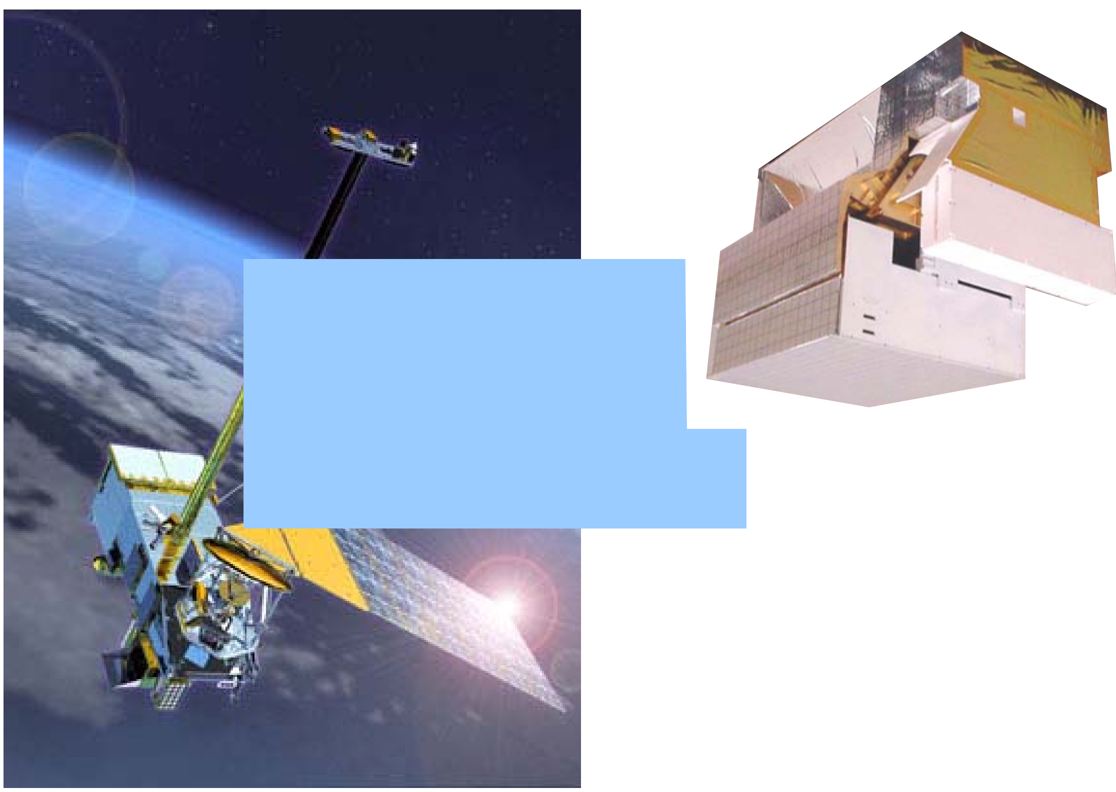
Abstract

The Crosstrack Infrared Sounder (CrIS) instrument is a meteorological sensor developed by ITT Industries, Space System Division for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program scheduled for launch in 2006. The sensor is part of the United States' national asset of spaceflight weather observing instruments used in collecting atmospheric data (temperature, moisture, and pressure) for weather modeling and forecasting.

To perform its mission, the CrIS sensor must insure high radiometric and spectral performance following the rigors of launch and the demands of a polar orbit environment. The CrIS sensor relies on its mechanical architecture to maintain precise alignment of the many optical components comprising the instrument. The sensor structure must be strong enough to survive the vibration of launch, stiff enough to maintain precise optical alignment, and compliant enough not to induce distortion over a wide operating temperature range. To achieve the optimal design solution the structural performance for each environment must be balanced.

This paper describes the Taguchi Parameter Design technique successfully implemented to develop an optimal mechanical instrument design for the CrIS sensor. Utilizing finite element analysis (FEA) with an L18 orthogonal array and monitoring vibration response (Grms), a 20 percent reduction in the sensor's reaction to launch vibration input was achieved.



Introduction

The Crosstrack Infrared Sounder (CrIS) sensor is designed and manufactured by ITT Industries, Space System Division (SSD). Approximately 1,800 employees, consisting of scientists, engineers, technicians, and support personnel fabricate spaceborne metrological and surveillance sensors and generated 2003 revenues of $1.8 billion. The Fort Wayne, Indiana facility of SSD (figure 1) has a long history of building weather observing sensors that operate in polar and geostationary orbits which dates back to the early 1960s. The most notable of ITT sensors is the GOES (Geostationary Operational Environmental Satellite) Imager series which continues to produces the visible imagery of clouds seen daily on the Weather Channel.

The CrIS sensor (figure 2) is the next generation of sounding radiometers which operates in a polar orbit, providing atmosphere temperature and pressure profile information. The sensor will fly on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) which is the follow-on to the Polar Operational Environmental Satellite (POES) mission.

Figure 1: SSD Facility located in Fort Wayne, Indiana

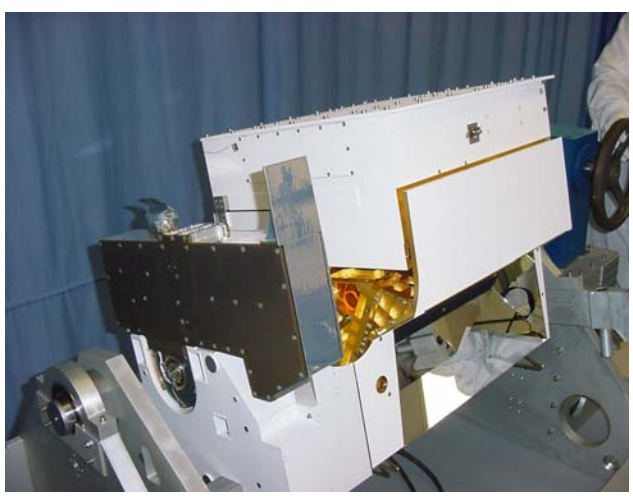


Figure 2: CrIS Sensor (Engineering Development Unit 2)

Background

The primary function of the CrIS radiometer is to convert scene radiance (earth view) to a calibrated electrical signal (i.e. photons to electrons). The physical hardware required for this conversion is a combination of optical, electromechanical and electrical components packaged together to form a sensor. To collect the earth scene energy, the sensor is launched into a low-earth polar orbit.

To achieve high fidelity calibrated signal data from an optical instrument requires maintaining stringent optical alignment from the input aperture, along the entire optical train, to the photon sensing detector arrays. Along the optical path a myriad of optical elements are held in mechanical mounts. The individual optical elements are grouped into modules, which are then combined to complete the sensor. In addition to the optomechanical hardware, the electronic components are mounted onto circuit card assemblies (CCAs) which are retained in electronic enclosures. These hardware modules must be integrated (packaged) together in such a manner as to properly function after sustaining the launch environment required to station the radiometer for earth observing. The mechanical system architecture selected and its robust design against launch vibration inputs is a significant contributor in achieving successful operational performance.

In a perfect optical system there would only be optical elements aligned motionless in space. Stresses would not be induced to disturb the various optical surfaces, which would alter wavefront and boresight. A true stress free mounting of the optics would exist. In reality, optical elements must be built and aligned under the influences of gravity and endure a harsh, stress inducing, environment in transit to space. ITT utilizes two basic principles to sustain optical alignment; employ stress-free optomechanical mounting techniques, and minimize loads in alignment sensitive devices. Techniques such as athermal optical element mounts and flexure mounts facilitate stress-free mechanical interface connections. Controlling thermal distortion and attenuating vibration inputs minimize the transmission of loads into alignment sensitive components.

Figure 3 details the mechanical configuration of the CrIS sensor hardware and highlights the nine major modules in the instrument. The illustration identifies the optical, electrical, and structural modules of the instrument. The Scene Selection Module (SSM), Interferometer, Telescope, Aft Optics and Detector Cooler complete the optical portion of the instrument. The Processor and Control Electronics (PCE) module contains the command and control electronics. The Instrument Frame and Optical Bench combine to form the instrument structure to which the aforementioned modules attach.

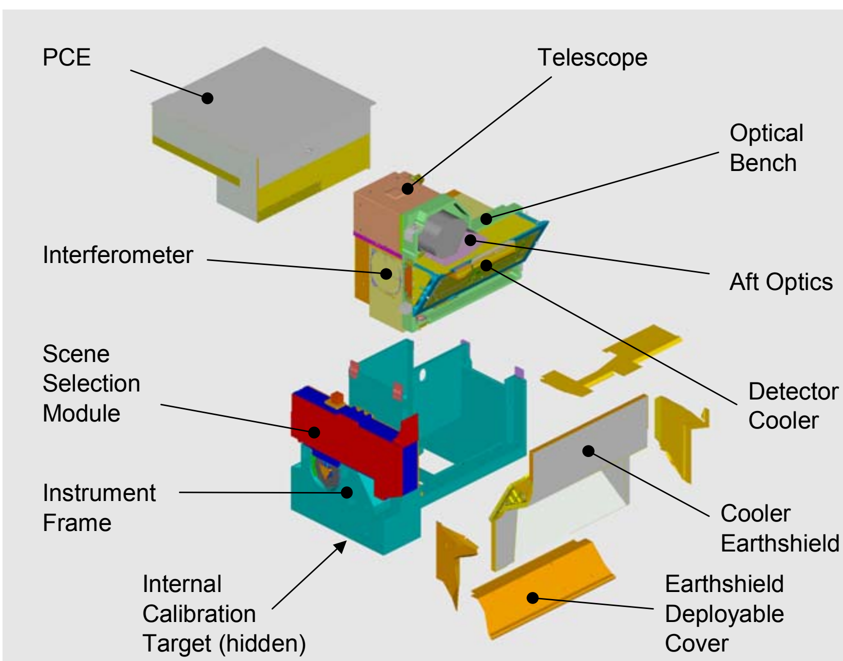


Figure 3: Exploded view of CrIS Sensor, EDU2

The top-level mechanical system architecture packages the optical subassemblies onto the optical bench portion of the instrument structure. This assembly strategy facilitates co-registration alignment between the telescope, aft optics and detector cooler (which houses the detector optics). The attachment of the optical bench (termed supermodule when fully populated with the aforementioned modules) and the SSM to the instrument frame completes the optical system. Alignment between the SSM and supermodule is an instrument field-of-view (FOV) pointing attribute. Figure 4 outlines the functions of the optical modules and the supporting instrument Structure function.

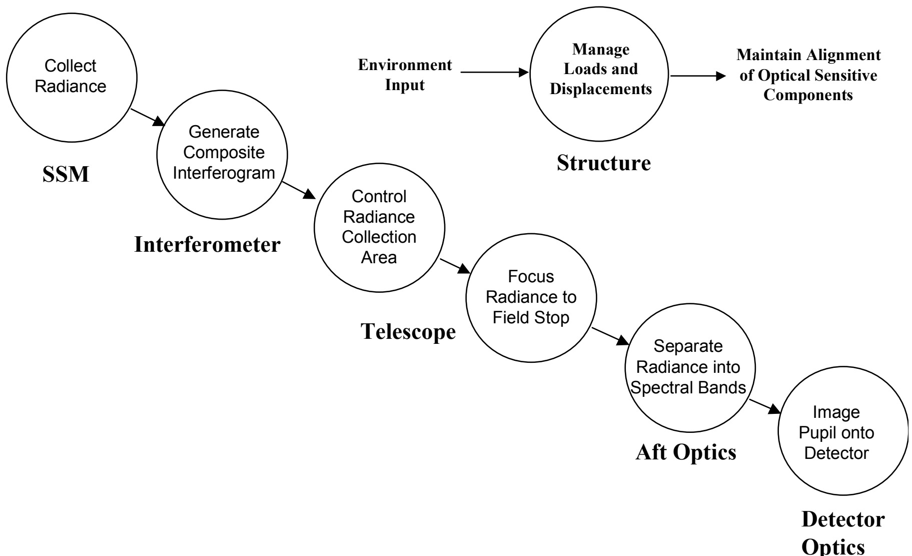


Figure 4: CrIS Sensor Function Diagram

The mechanical packaging of an optical instrument distills down to the trade between the optical system aperture size against the allowable mechanical volume. The science of the instrument seeks to maximize the aperture. The mechanical engineering challenge is to accommodate the optics within the allowable volume and provide the associated mountings of the elements. This includes packaging of the electronic and electromechanical components. The desired mechanical architecture maintains the instrument wavefront and boresight requirements when subjected to the rigors of the launch and on-orbit environments. Subsequently, a robust mechanical architecture is one that is insensitive to the influences of these inputs.

The CrIS instrument launch environment is between 0-2000 Hz with an average energy input of 8 Grms. The maximum energy input is between 50 and 800 Hz, and as such, it is desired to have the natural frequency of components and subassemblies above this range. The reality of the geometric and material configurations of most subassemblies will yield natural frequencies (modes) within this range. The engineering challenge arises in managing these modes, namely preventing instrument self-excitation of a module from exciting adjacent module(s) and the associated undesirable loads. Good design practice places a square root of 2 separation in natural frequencies between adjoining modules. Providing optimal mode separation and vibration response attenuation, in a cost-effective sensor construction, is the focus of this Taguchi Parameter Design study.

Objective

The objective of the Taguchi study was to refine the initial engineering development design to a final flight design solution insensitive to vibration input. Thereby, eliminating the need for expensive mechanical fastening systems required to carry large structural loads.

Two significant manufacturing related observations were made during the build of the CrIS engineering development unit (EDU2); the need for ultra-high (yield) strength fasteners securing the connection between PCE and instrument frame, and the need for high (yield) strength fasteners securing the telescope mirrors to the telescope housing. The first issue required unachievable assembly techniques; that is, the assembly torque was so large that tooling would break and the required fastener preloads were not achieved. The second issue manifested into mirror distortion as the mounting fastener imbedded and yielded the mirror mount. These unusually excessive fastener loads were the result of the CrIS instrument's vibration response. Structural analysis highlighted the stacking of mode response between physically adjacent/adjoining modules. Figure 5 maps the first mode natural frequencies of principle components and subassemblies of the EDU2 instrument and identifies the two problem areas.

Evaluation of the module natural frequency distribution highlights the interaction of the telescope attached to the optical bench, in that at starting around 150 Hz (broad peaks) the entire supermodule (optical bench, interferometer, telescope, and cooler) and frame becomes active. The results; high loads within the telescope requiring high fastener torque (preloads) to secure the optics to the telescope housing, and due to the mechanical connection to the PCE an excitation of the PCE mass which manifest into high loads at the PCE interface to instrument frame. In summary, the close grouping of natural frequencies yielded a high Grms instrument response.

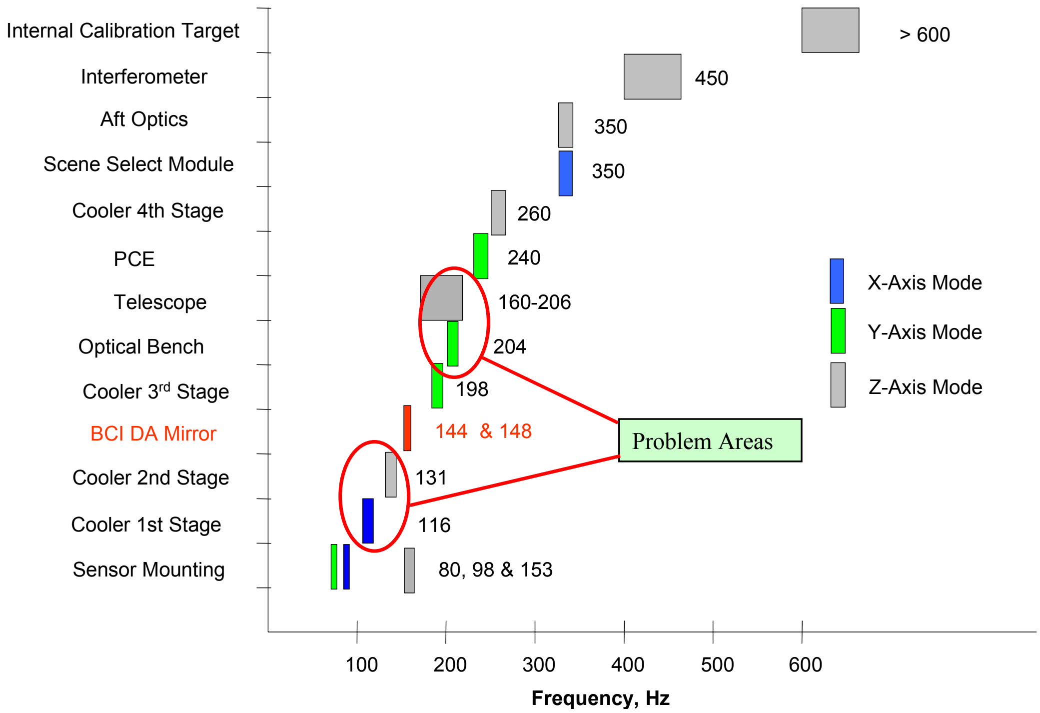


Figure 5: CrIS EDU2 module and component natural frequency mode map

Approach

Taguchi Parameter Design approach utilized CrIS system finite element model computer simulations. Figure 6 highlights the Parameter diagram, indicating the noise and control factors influencing the function of the instrument structure. The experiment utilized an L18 orthogonal array and measured the Grms vibration responses of the sensor in the three principal axes of launch vibration excitation. S/N ratios were calculated as smaller-the-better. Two damping conditions were also contained in the outer array to represent the instrument with and without external damping treatments. The vibration analyses were conducted using Nastran and spreadsheets were utilized to process the voluminous output. Two experiments were performed, the second experiment improving upon the findings of the first.

The quality factor that is measured during the Parameter Design study is Grms response. Reiterating the study objective; to develop an instrument architecture that is robust (insensitive) to vibration input, effectively reducing the acceleration and associated interface loads within the EDU structure. The expectation is to reduce the interface loads such that two classes of fasteners are utilized in the flight instrument build. The first class, moderate strength (yield) fasteners (60 ksi) would be utilized within modules. Examples are the fasteners securing mirrors (optics) to their module housing. The second class, high strength fasteners (120 ksi) used at module-to-module interfaces. Examples are the fasteners securing the telescope module to optical bench. Ultra-high strength (170 ksi) fasteners were no longer desired in the design.

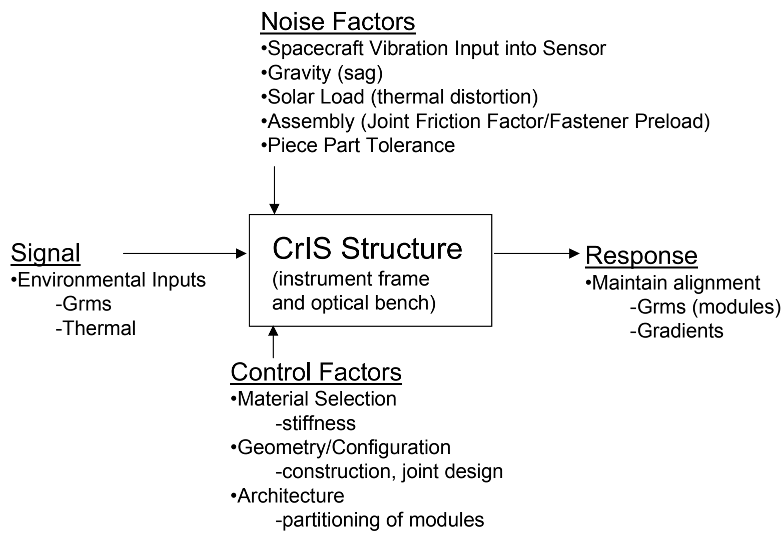


Figure 6: CrIS Structure Parameter Diagram

Results

To capture the control factors (hardware attributes that the engineering staff may change) an L18 array is used. Eight (8) factors are tuned, one (1) factor may be altered in two different configurations, the remaining seven (7) factors in three configurations. Table 1 details the inner array. The bold notation in Table 1 indicates the EDU baseline configuration. The noise factor (external influences that the engineering staff can not necessarily control) is the launch vibration input (8 Grms over 20-2000 Hz, in X, Y, and Z). The system damping was modeled in two ways; light damping (2 percent flat between 1 – 2000 Hz), and high damping (10 percent slope to 0.5 percent between 1-2000 Hz). The intent is to construct a system architecture that minimizes the input-output function. Subsequently, a smaller-the-better S/N ratio is desired.

Table 1: L18 Array

L18 Array: 1 - 2 level factor, 7 - 3 level factors

	Factor	Level 1	Level 2	Level3
PCE:	A	**on structure**	off structure	
Frame Material:	B	Aluminum	**Beralcast**	Beryllium
Main Flexure Stiffness:	C	-50%	**Present**	+50%
Bench Flexure Stiffness:	D	-50%	**Present**	+50%
PCE Mount Stiffness:	E	**Present**	-50%	-90%
Cooler Stage 1 Flexures:	F	-50%	**Present**	+50%
Cooler Stage 2 Flexures:	G	-50%	**Present**	+50%
Telescope Construction:	H	**Aluminum**	Beralcast	Beryllium

Blue notates baseline configuration

Analysis

For the Taguchi Analysis the method of simulation was performed utilizing Nastran finite element modeling. Eighteen modal solution cases up to 1000 Hz were run, each either 2 percent constant damping or 10 percent sloped damping. Each run included 3 axes of random input (X, Y, and Z). Response of the complete sensor finite element model was measured at 36 specific locations. Table 2 details the distribution of the measured response. The experimental results are listed in table 3 and figure 7.

Table 2: Data recovery within Nastran FEA

Location	No. of Responses Measured	Percentage
Frame	5	14%
Bench	3	8.3%
Cooler	14	39%
Telescope	6	16.7%
Interferometer	5	14%
Scene Selection Module	1	2.7%
	36	100%

Table 3: Signal/Noise Ratio and Grms Response

Smaller the Better S/N Ratio	Grms Mean	A	B	C	D	E	F	G	H	Experiment No.
-20.358	8.173	1	1	1	1	1	1	1	1	1
-20.440	8.359	1	1	2	2	2	2	2	2	2
-20.612	8.555	1	1	3	3	3	3	3	3	3
-21.402	9.328	1	2	1	1	2	2	3	3	4
-21.578	9.651	1	2	2	2	3	3	1	1	5
-22.569	10.563	1	2	3	3	1	1	2	2	6
-21.772	9.753	1	3	1	2	1	3	2	3	7
-22.710	10.822	1	3	2	3	2	1	3	1	8
-22.366	10.362	1	3	3	1	3	2	1	2	9
-21.442	9.014	2	1	1	3	3	2	2	1	10
-21.340	9.146	2	1	2	1	1	3	3	2	11
-21.514	9.154	2	1	3	2	2	1	1	3	12
-22.376	9.983	2	2	1	2	3	1	3	2	13
-22.382	10.474	2	2	2	3	1	2	1	3	14
-22.812	10.933	2	2	3	1	2	3	2	1	15
-22.179	10.128	2	3	1	3	2	3	1	2	16
-22.949	10.908	2	3	2	1	3	1	2	3	17
-23.538	11.781	2	3	3	2	1	2	3	1	18
-21.908	**9.838**									
-22.038	10.092	1	2	2	2	1	2	2	1	Baseline

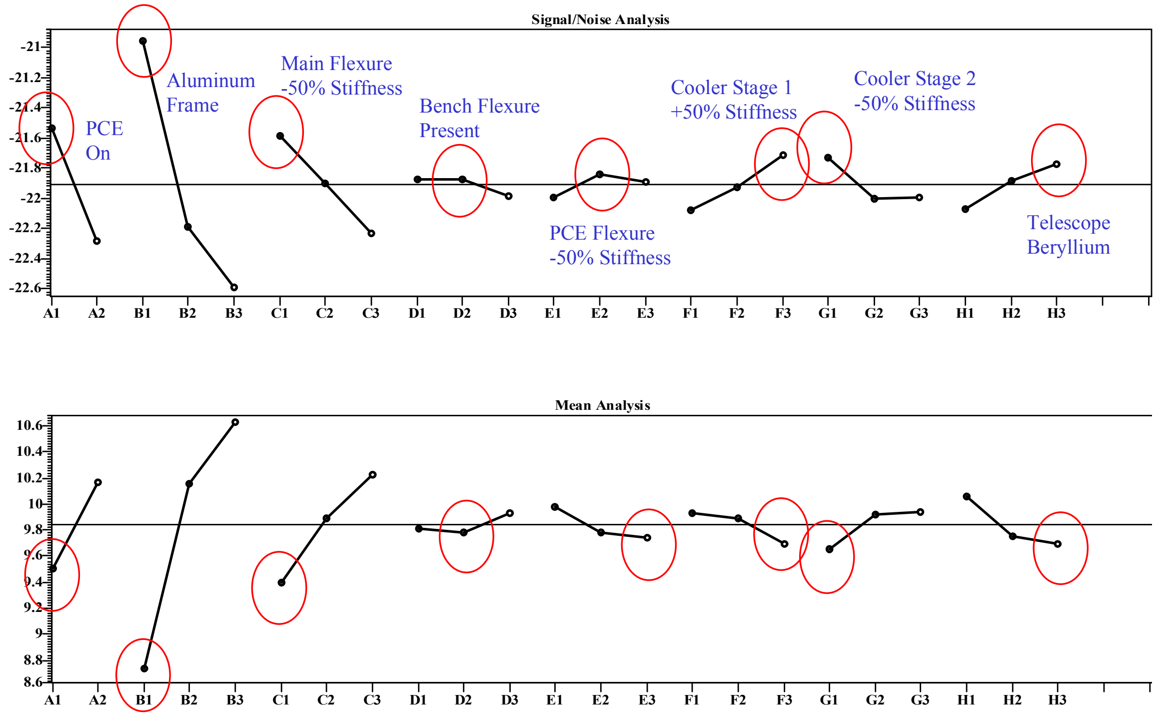


Figure 7: Smaller the Better; S/N and Grms Response

The principle findings of the Taguchi Analysis emphasized utilizing a soft structure (aluminum instrument frame) and stiff modules (beryllium telescope). This makes sense from a mode separation standpoint. The sensor's first structural mode reduced from 82Hz to 58Hz (minimum allowable first mode is 50Hz per specification).

Confirmation

Following the Taguchi Analysis additional configuration were explored to expand the understanding of the sensor architecture. Detail design changes (i.e., changing material type of the frame and optical bench flexures, etc…) were investigated and compared against the baseline. Table 4 details the candidate configurations, with figure 8 detailing the associated signal-to-noise and Grms response. Comparing the confirmation case (choosing the optimal control factor settings) yielded approximately 22 percent reduction in Grms, 7.85 Grms as compared to the EDU2 baseline instrument configuration of 10.09 Grms. The analysis demonstrated that the mass of the PCE could be accommodated in the design and that tuning the stiffness of the instrument frame and flexures reduced the fastener loads between the PCE and instrument frame. Figure 9 highlights the system performance of the CrIS EDU3 structure and the elimination of undesired modal interaction.

Table 4: CrIS Sensor Configurations

	EDU2 Baseline	EDU2 Optimized	EDU3 – December 2002
Frame:	AM-162	Aluminum	AM-162
Main Flexures	(6) – 2 mm Blades	(6) – 1.5 mm Blades	(4) – 1.5 mm Blades
Op Bench	Beryllium	Beryllium	Beryllium
Bench Flexures	baseline	baseline	stiffer
Telescope	Aluminum	Beryllium	Beryllium
Cooler	Aluminum 3 & 4	Aluminum 3 & 4	Beryllium 3 & 4
Cooler Flexures	baseline	stiff 1, soft 2	soft 1, stiff 2
PCE	baseline	baseline	1394 Radiator & ext. IE box
PCE Mounts	baseline	softer	stiffer
BCI	baseline	baseline	baseline – tune DA modes
SSM/ICT	baseline	baseline	baseline

Module	EDU2 Baseline (Grms)	Location	EDU3 Dec-2002 (Grms)	Location	Percent Reduction
SSM	13.28	Z-axis, Y response	11.18	Z-axis, Y response	**15.8**
ICT	11.33	Z-axis, Z response	8.52	Z-axis, Z response	**24.8**
Optical Bench	8.40	Z-axis, Z response	7.34	Z-axis, Z response	**12.6**
PCE	8.54	Z-axis, Z response	8.35	Y-axis, Y response	**2.2**
Frame	7.81	Z-axis, Z response	6.55	Z-axis, Z response	**16.1**
Cooler	8.76	Z-axis, Z response	7.00	Z-axis, Z response	**20.1**
Telescope	11.62	X-axis, Y response	10.08	Y-axis, Y response	**13.3**
Interferometer	8.55	Z-axis, Z response	7.29	Y-axis, Y response	**14.7**
Aft Optics	15.87	Z-axis, Z response	15.13	X-axis, X response	**4.7**
Sub-Patch	45.77	Y-axis, Y response	35.67	Z-axis, Y response	**22.1**
Patch	37.48	X-axis, X response	26.08	X-axis, X response	**30.4**
Radiator	30.13	X-axis, X response	22.55	X-axis, X response	**25.2**
Vacuum Housing	13.41	Z-axis, Z response	13.84	X-axis, X response	**-3.2**
Average	17.00		13.81		**18.7**

Figure 8: Sensor Configuration Data Summary

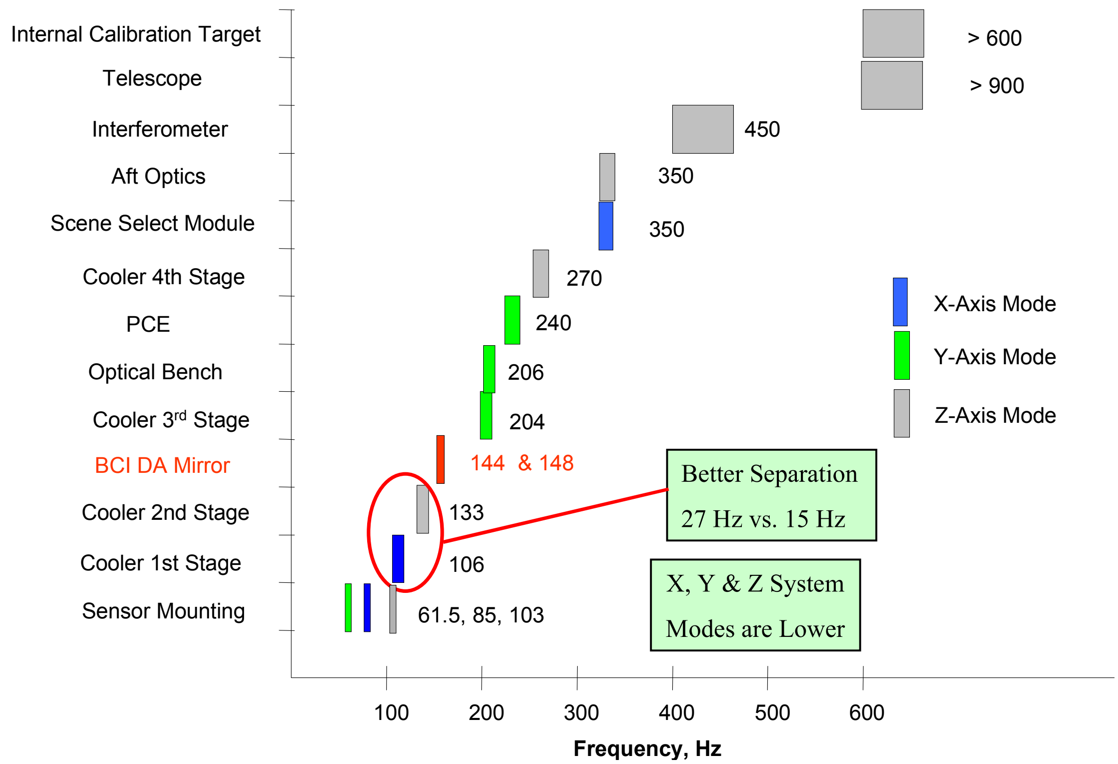


Figure 9: CrIS EDU3 module and component natural frequency mode map

Conclusions

The Taguchi Analysis effort has worked well in establishing the performance and boundaries of the CrIS hardware design. It has clearly validated the strategy of separating the natural frequency modes of the modules in achieving a reduced response. The ultra-high interface loads, and the associated undesirable fastener implementation, have been eliminated. Proposed changes to the instrument frame are producible and the associated stress levels remain within acceptable design limits. Changing to the all-beryllium telescope has eliminated the high loads experienced at the optical components as the result of the previous dynamic coupling with the optical bench. The analysis also highlights the tuning within the cooler, both to individual stage supports and material change (aluminum to beryllium), to reduce internal interface loads.

The robust design effort has successfully accomplished the objective of reducing the overall Grms response of the CrIS sensor. The tool has worked well to aid in tuning the sensitivity of the sensor structural response to the launch environment.

Acknowledgements

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